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Modeling the contribution of abiotic exchange to CO_2 flux in alkaline soils of arid areas

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Abstract: Recent studies on alkaline soils of arid areas suggest a possible contribution of abiotic exchange to soil CO_2 flux (F_c). However, both the overall contribution of abiotic CO_2 exchange and its drivers remain unknown. Here we analyzed the environmental variables suggested as possible drivers by previous studies and constructed a function of these variables to model the contribution of abiotic exchange to F_c in alkaline soils of arid areas. An automated flux system was employed to measure F_c in the Manas River Basin of Xinjiang Uygur autonomous region, China. Soil pH, soil temperature at 0–5 cm (T_s), soil volumetric water content at 0–5 cm (θ_s) and air temperature at 10 cm above the soil surface (T_{as}) were simultaneously analyzed. Results highlight reduced sensitivity of F_c to T_s and good prediction of F_c by the model $F_c=R_{10}Q_{10}^{(Tas-10)/10}+r_7q_7^{(pH-7)}+\lambda T_{as}+\mu\theta_s+e$ which represents F_c as a sum of biotic and abiotic components. This presents an approximate method to quantify the contribution of soil abiotic CO_2 exchange to F_c in alkaline soils of arid areas.

Keywords: soil respiration; temperature sensitivity; Q_{10} model; soil abiotic CO_2 exchange; soil alkalinity

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Carbon dioxide flux in soil respiration (F_c, soil CO_2 flux) plays a significant role in the terrestrial ecosystem carbon cycle and accounts for 60%–90% of the total ecosystem respiration (Schimel et al., 2001). Soil is a porous and complex system and the time lag between F_c (the "apparent" respiration) and the real soil respiration remains undetermined (Fang et al., 1999). This time lag is non-negligible unless the measuring period is larger than one year (Raich and Schlesinger, 1992). The contributions of root respiration and the deep circulation of organic matter in soils associated with roots raise uncertainty during the determination of whether soil is a source or sink of the atmospheric CO_2 (Högberg et al., 2001; Nguyen, 2003; Giardina et al., 2004).

Estimation of carbon dioxide flux in soil respiration is considerably uncertain. During the last three decades, soil respiration was thought to be sensitive to the dramatic temperature increases ongoing in this century (IPCC, 2007). Researchers worldwide calculate estimates of Q_{10}, a factor by which respiration is multiplied when temperature increases by 10°C, but few publications stated which environmental variables determine the spatial variations of the apparent Q_{10}. Other environmental factors also change simultaneously with temperature and thus obscure the effect of temperature (Davidson and Janssens, 2006). The climate change and vegetation seasonality might contribute an ecological gradient in the Q_{10} value (Wang et al., 2010).

Meanwhile, other researchers revealed a series of "anomalous" CO_2 fluxes in soil respiration of carbonate ecosystems (Hastings et al., 2005; Jasoni et al., 2005; Mielnick et al., 2005; Wohlfahrt et al., 2008), some of which were explained in terms of abiotic processes (Emmerich, 2003; Mielnick et al., 2005;

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Kowalski et al., 2008). Further research is still necessary to investigate whether these processes are significant in terrestrial CO_2 sinks (Schlesinger et al., 2009), but they can temporally dominate the ecosystem respiration (Inglima et al., 2009), reducing the robustness of the Q_{10} model (Sanchez-Cañete et al., 2011). This may reveal some unknown components of soil respiration and motivate the model development (Kowalski et al., 2008).

One of these abiotic processes was successfully separated following soil sterilization, implying a potential soil alkalinity contribution to the soil carbon cycle in alkaline land (Stone, 2008; Xie et al., 2009), similar to ocean pH contribution to the ocean carbon cycle (Caldeira et al., 2003). As a strong (or temporally strong) ecological process, the separated abiotic process contributed to carbon dioxide flux in soil respiration at alkaline sites of arid areas (Xie et al., 2009). This suggested soil pH as an additional determinant of the apparent soil respiration in alkaline land since soil pH determines the intensity of abiotic CO_2 exchange. Furthermore, soil pH is also a main determinant of the real soil respiration. It has been widely accepted as a dominant factor that regulates soil nutrient bioavailability, vegetation community structure, plant primary productivity, and a range of carbon processes, including microbial community structure and activity (Robson, 1989). Soil pH affects soil features, soil validity and soil transformation, and impacts soil organic matter mineralization (Laskowshi et al., 2003; Kermitt, 2006). The processes such as nitrification are considered to be highly pH sensitive (Curtin et al., 1998). Alkalinity influences the formation, properties and development of soils and affects the soil microbial activity and normal growth of crops. This situation can be attributed to the effects of high soil salinity content on soil enzyme and microorganism activity. Alkalinity is recognized as a dominant factor that governs the microbial turnover of organic matter (Adams and Adams, 1983) and produces an inhibitory effect on the rate of decomposition of organic matter (Olsen et al., 1996).

Soil temperature and soil water content was suggested as the other two main determinants of soil CO_2 flux in alkaline soils of arid areas (Xie et al., 2009), and air temperature was thought to be a main driver of the abiotic ventilation of CO_2 (Serrano-Ortiz et al., 2010). However, both the overall contribution of abiotic CO_2 exchange and its drivers remain unknown. The objectives of this research are to analyze the environmental variables suggested as possible drivers by previous studies and construct a function of these variables to estimate soil CO_2 flux in alkaline soils of arid areas, which also presents an approximate method to quantify the contribution of soil abiotic CO_2 exchange to the CO_2 flux in alkaline soils of arid areas.

1 Materials and methods

1.1 Study area

The experiments were conducted at the Manas River Basin of Xinjiang Uygur autonomous region, China, which is located at the southern periphery of the Gubantonggut Desert and in the hinterland of the Eurasian continent. Soils in the hinterland of the Eurasian continent bear typical physical and chemical characteristics due to the soil water and soil salt being transported during complex ecological processes. Almost 10×10^6 km^2 of the region are arid land, occupying a third of the global total. The largest desert-oasis compound system in the world developed in this vast alkaline region. The inflow rivers carried large quantities of salt into the desert-oasis compound ecosystem, resulting in strong, complicated ecological responses (Chen et al., 2005; Xu et al., 2007). Soil samples analyses in this region revealed the extreme alkalinity of local soils, with pH values of 8.4–9.6 (Zhu et al., 2011). This pH range exceeds the average alkalinity of the outflow rivers (pH: 8.1). High efficiency in water use and carbon gain is a specific characteristic of the regional carbon cycle and water cycle (Liu et al., 2011; Liu et al., 2012a; Ma et al., 2012).

1.2 Field experiments

Field experiments were conducted at six sampling sites (Fig. 1) during July 2012. The experiment conditions were very different at each site. Soil CO_2 flux (F_c) was measured with an LI-8100 Automated Soil CO_2 Flux System (LI-COR, Lincoln, Nebraska, USA) equipped with a long-term monitoring chamber (LI-8100 L), began at 06:00 a.m. and ended at 06:00 a.m. (local time) on the next day, with an interval of 1′20″. Some of these observations focused on the nocturnal variations of F_c, to investigate the universality of the nocturnal CO_2 absorption in summer in Gurbantunggut Desert and other arid regions (Stone, 2008). The air temperature of 10 cm above the soil surface (T_{as}), the soil temperature (T_s) and the soil water content (θ_s) at 0–5 cm depth were monitored automatically by temperature probes equipped with a LI-8100 System.

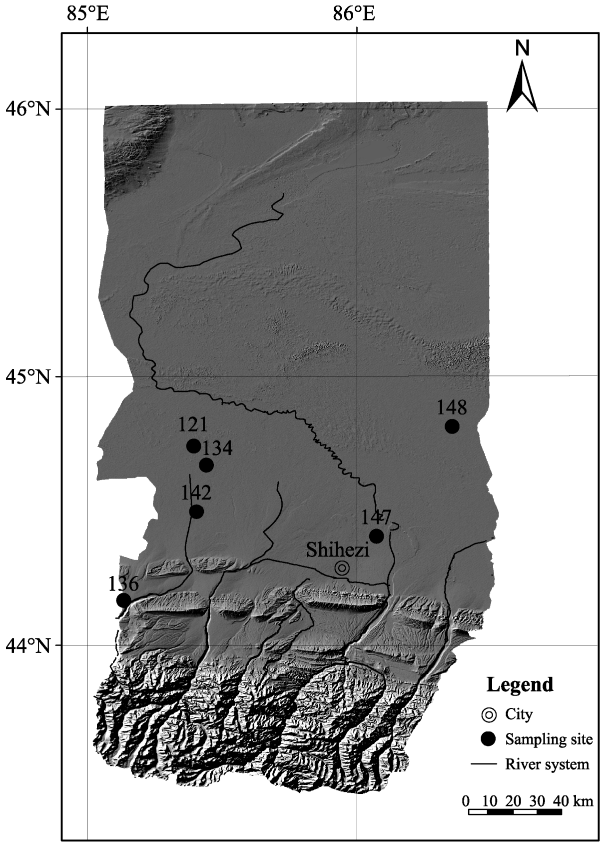

Fig. 1 Regional distribution of the sampling sites in the Manas River Basin

Descriptive statistics were used to calculate averages of the data from each set of reduplicates at a site scale. For a regional scale, we calculated averages along the gradient of soil pH. A series of field data and laboratory data of F_c in Sangong River Basin were collected from previous publications (Li et al., 2011; Chen et al., 2012; Liu et al., 2012b; Ma et al., 2012), and some of these data were included in our modeling approach.

1.3 Modeling approach

The model of F_c in the present study is developed from the worldwide utilized Q_{10} model for the estimation of carbon dioxide flux in soil respiration (Wang et al., 2010):

$$F_a = R_{10} \times Q_{10}{}^{(T-10)/10} \quad (1)$$

Where T=T_s or T_{as}, R_{10} is the referred F_a at 10°C, and Q_{10} is the factor by which F_a is multiplied when T increases by 10°C.

An explicit analysis of the components of F_c in alkaline areas within a growing season suggests a reconciliation of Eq. 1 as suggested by Chen et al. (2012):

$$F_c = R_{10} \times Q_{10}{}^{(T-10)/10} + F_x. \quad (2)$$

Where F_x is the contribution of abiotic CO_2 exchange to F_c.

Because soil pH explained the spatial variations of F_x (Chen et al., 2012) and laboratory experiments suggested a linear model for F_x (Xie et al., 2009), the pH submodel (referring to the function form of Q_{10} model) was chosen from two function forms:

$$f(\text{pH}) = r_7 q_7{}^{\text{pH}-7} \quad \text{and} \quad f(\text{pH}) = \gamma\text{pH},$$

and Eq. 2 was represented as:

$$\begin{cases} F_c = F_a + F_x \\ F_a = R_{10} Q_{10}{}^{(T-10)/10} \\ F_x = f(pH) + \lambda T + \mu\theta_S + e. \end{cases} \quad (3)$$

Where r_7 is the referred value of f(pH) at pH=7; q_7 is the factor by which f(pH) is multiplied when pH increases by 1; and λ, μ and e are regression coefficients. It must be noted that the experimental partition of biotic and abiotic components of F_c is still an unresolved issue (Chen et al., 2012). So we employed a global convergent Q_{10}=1.5 (Mahecha et al., 2010) to reduce the uncertainty and increase the comparability of our analyses with other arid regions. The other parameters of Eq. 3 were stepwise fitted. R_{10} was determined first and the data beyond explanation of the Q_{10} model was attributed to F_x. Then the parameters in f(pH) were fitted to determine the pH submodel. The regression coefficients λ, μ and e were finally determined.

2 Results

2.1 Variations of F_c

Variations of F_c with soil temperature at 0–5 cm revealed that F_c has reduced sensitivity to T_s with seasonal variability along two ecological gradients (soil alkalization and vegetation seasonality). This is more evident in saline desert than in oasis farmland (Fig. 2), implying that soil abiotic CO_2 exchange results in the reduced sensitivity of F_c to T_s. Alkaline-saline desert has a higher alkalization degree and lower vegetation coverage, and the soil alkalization degree, and vegetation coverage determine the dominance of biotic and abiotic processes.

F_c is more sensitive to T_{as} than to T_s and θ_s on clear days, and so T_{as} is an optimal temperature index to be introduced in Eq. 3, but the relationship between F_c and θ_s becomes much more robust on the days before or after a rain pulse. This explains the necessity to further consider θ_s as a determinant of F_c in Eq. 3 (Fig. 3).

2.2 Simulation of F_c

An analysis with a back-propagation network according to the distribution of residuals and the performance of the cross-validation in the network proved the reliability of utilizing pH, T_{as} and θ_s to determine F_c. These optimal indices explain approximately 90% of the variability of F_c (Figs. 4 and 5). Soil pH primarily determines the spatial variations of F_c, while T_{as} and θ_s explain a significant amount of the F_c temporal variations.

Performance of Eq. 3 with linear f(pH) and exponential f(pH) on a site scale (farmland, desert, farmland+desert) and a regional scale (Sangong River Basin, Sangong River Basin+Manas River Basin, Sangong River Basin+Manas River Basin+Laboratory) demonstrated that Eq. 3 with exponential f(pH) is more suitable in the description of F_c (Fig. 6). Although Eq. 3 with linear f(pH) has a good prediction at a special alkaline site, it becomes not robust when considering two types of alkaline soils together. Equation 3 with exponential f(pH) is not only a good fit at different sites but also robust when calculated in the Sangong River Basin, the Manas River Basin and the coupling of two databases. Equation 3 with exponential f(pH) is even a good fit when the laboratory database is included with the two field databases, with a slightly lower estimation. Such a slightly lower estimation demonstrated the sensitivity of the parameters in Eq. 3 because biotic processes were depressed in the laboratory experiments.

2.3 Analyses

Variation of soil CO_2 flux (F_c) at alkaline sites of the

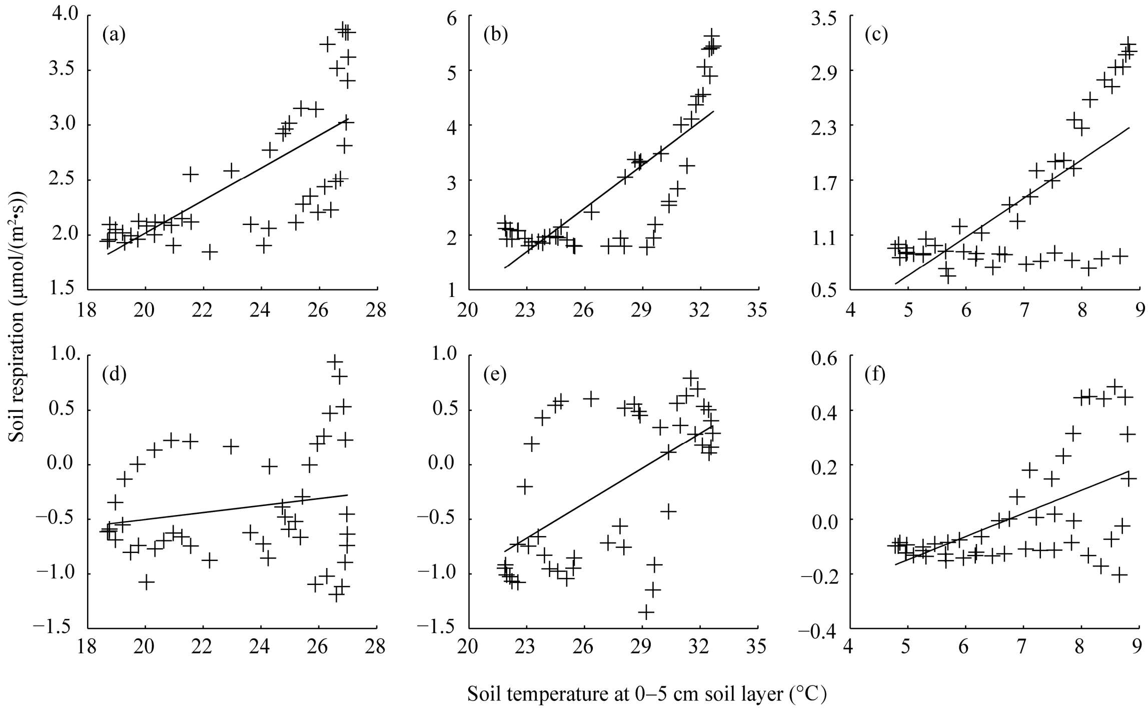

Fig. 2 Variations of respiration with soil temperature along double ecological gradients (the soil alkalization and the vegetation seasonality), where the soil alkalization in oasis farmland (a–c: pH 7.5) and alkaline-saline desert (d–f: pH 9.3) was compared. The vegetation gradient is naturally formed in the seasonal variations.

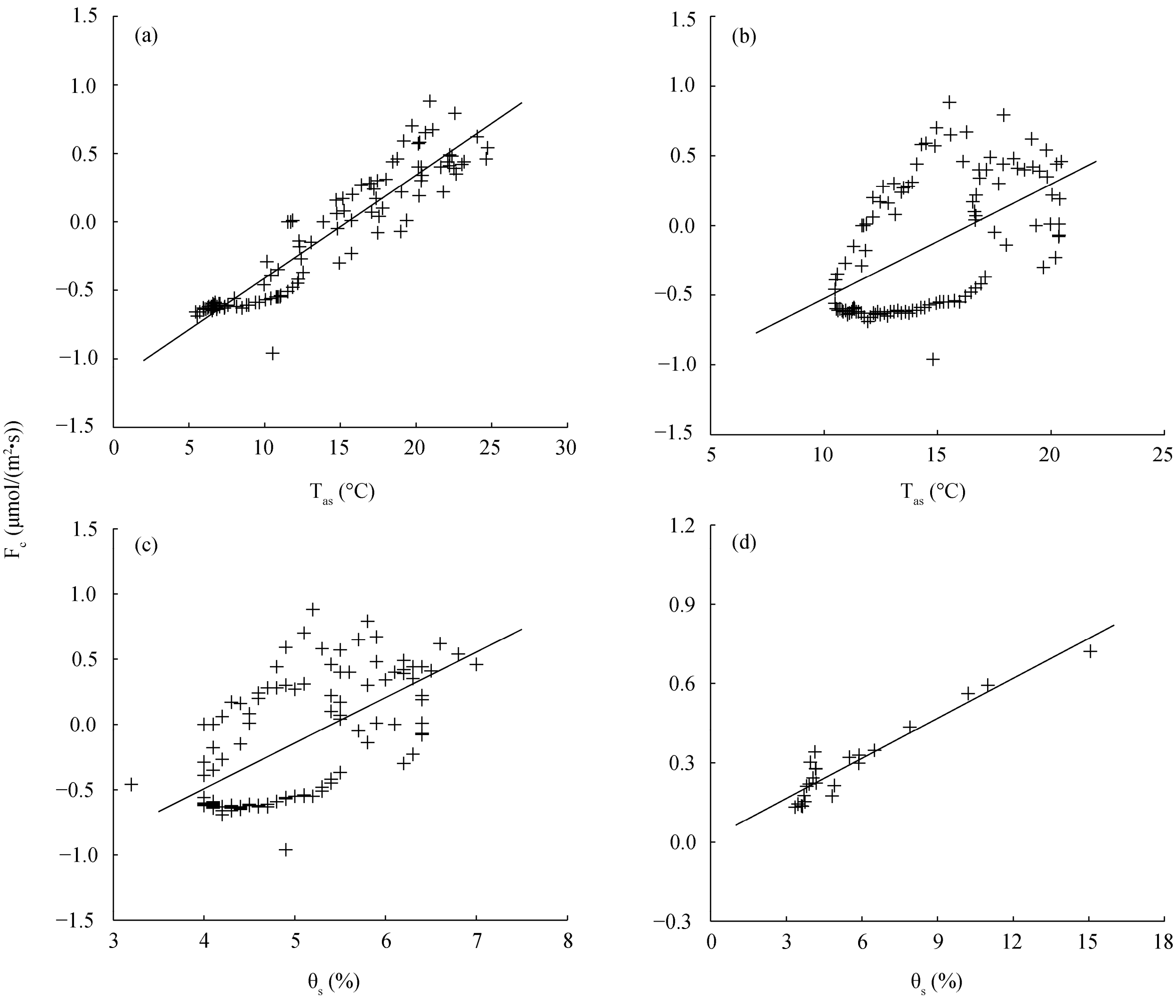

Fig. 3 Dependence of F_c on T_{as} and θ_s on clear days (a–b) and the relationship between F_c and θ_s on the days before and after a rain pulse (c–d)

arid area is mainly determined by soil pH, soil volumetric water content at 0–5 cm (θ_s) and air temperature at 10 cm above the soil surface (T_{as}). The model $F_c=R_{10}Q_{10}^{(T_{as}-10)/10}+r_7q_7^{(pH-7)}+\lambda T_{as}+\mu\theta_s+e$ has a better prediction of F_c than the model since the model with an exponential f(pH) is robust on both site and regional scales. Hence we suggest the former model as a suitable function to estimate F_c in alkaline soils of the arid area.

Parameters of the model were different on three regional-scale analysis (Sangong River Basin, Sangong River Basin+Manas River Basin, Sangong River Basin+Manas River Basin+Laboratory). The regional-scale analysis considering both Sangong River Basin and Manas River Basin presents the parameters most applicable in other arid regions, and the parameterized model is $F_c=0.3625\times 1.5^{(T_{as}-10)/10}+3.0191\times 0.7562^{pH-7}+0.0059T_{as}+0.0003\theta_s-2.5081$. This presents an approximate method to quantify the soil abiotic CO_2 exchange contributions by $F_x=3.0191\times 0.7562^{pH-7}+0.0059T_{as}+0.0003\theta_s-2.5081$.

Analyses in the present study suggest that soil biotic and abiotic CO_2 exchange have equal contributions to F_c, and therefore soil abiotic CO_2 exchange is a crucial component in the carbon balance in alkaline soils of the arid area. But it is considerably uncertain to determine whether alkaline soil is a source or sink of the atmospheric CO_2 since the deep circulation of soil inorganic/organic carbon associated with soil abiotic CO_2 exchange remains unknown.

3 Discussion

Soil respiration is the main process for underground

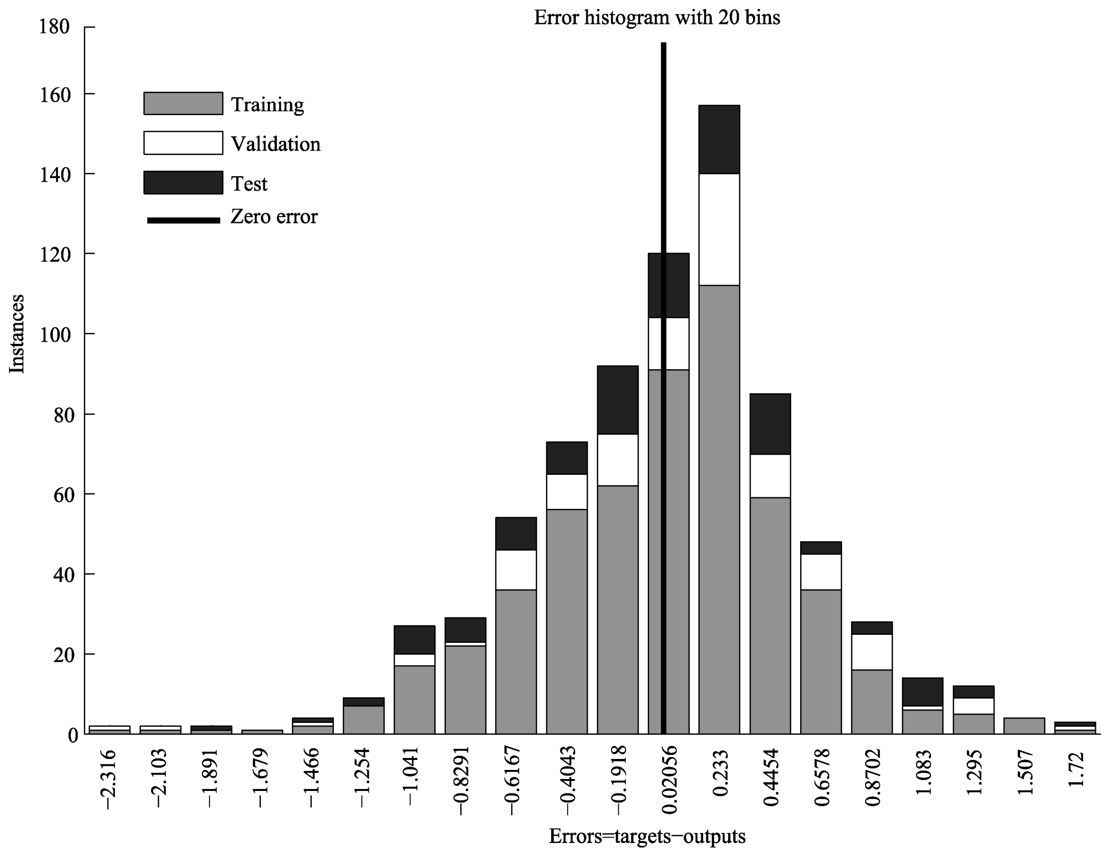

Fig. 4 The process of the investigation of the reliability of determining F_c by pH and T_{as} with a back-propagation network and the distribution of residuals (bars)

CO_2 release into the atmosphere. In the most recent publications, it was interpreted as the respiration of plant organs (autotrophic respiration) and the respiration of microbes and animals (heterotrophic respiration) (Nguyen, 2003), and estimated by measurements of soil CO_2 flux (Schimel et al., 2001). This research implies that soil abiotic CO_2 exchange is a crucial component of soil CO_2 flux in alkaline soils of an arid area and can explain the "anomalous" CO_2 fluxes in the apparent soil respiration.

The inherent spatial and temporal variations in data must be considered in the assessment of the sensitivity of environmental factors that influence ecological data (Legendre and Fortin, 1989; Butler and Chesson, 1990; Dutilleul, 1993; Underwood et al., 1996). Soil respiration depends on numerous complex and non-linear interactions between physiological, biochemical, chemical, ecological and meteorological variables (Schimel et al., 1994; Jarvis, 1995). Despite of the performance of Q_{10} model around the world, the advance in empirical modeling suggested the introduction of other drivers. Reth et al. (2005) identified the influence of soil chemistry (including soil pH) as an additional predictor and demonstrated the spatial variation of soil respiration in the studied field is significantly correlated with soil pH. We therefore included soil pH and the degree of soil alkalization as additional determinants of the "anonymous" component F_x in soil respiration in alkaline areas.

The introduction of F_x in our modeling of F_c can be considered as the description of the part of F_c unexplained by biological respiration components. The potential overlap in the temporal and spatial components of the ecological data leaves an unexplained component worthy of inclusion in the multivariate analysis of the ecological data (Borcard et al., 1992; Borcard and Legendre, 1994; Legendre and Borcard, 1994; Økland and Eilertsen, 1994; Anderson and Gribble, 1998; Borcard and Legendre, 2002). This overlap additionally illustrated why the spatial difference of abiotic components can be explained by pH, and not by temperature.

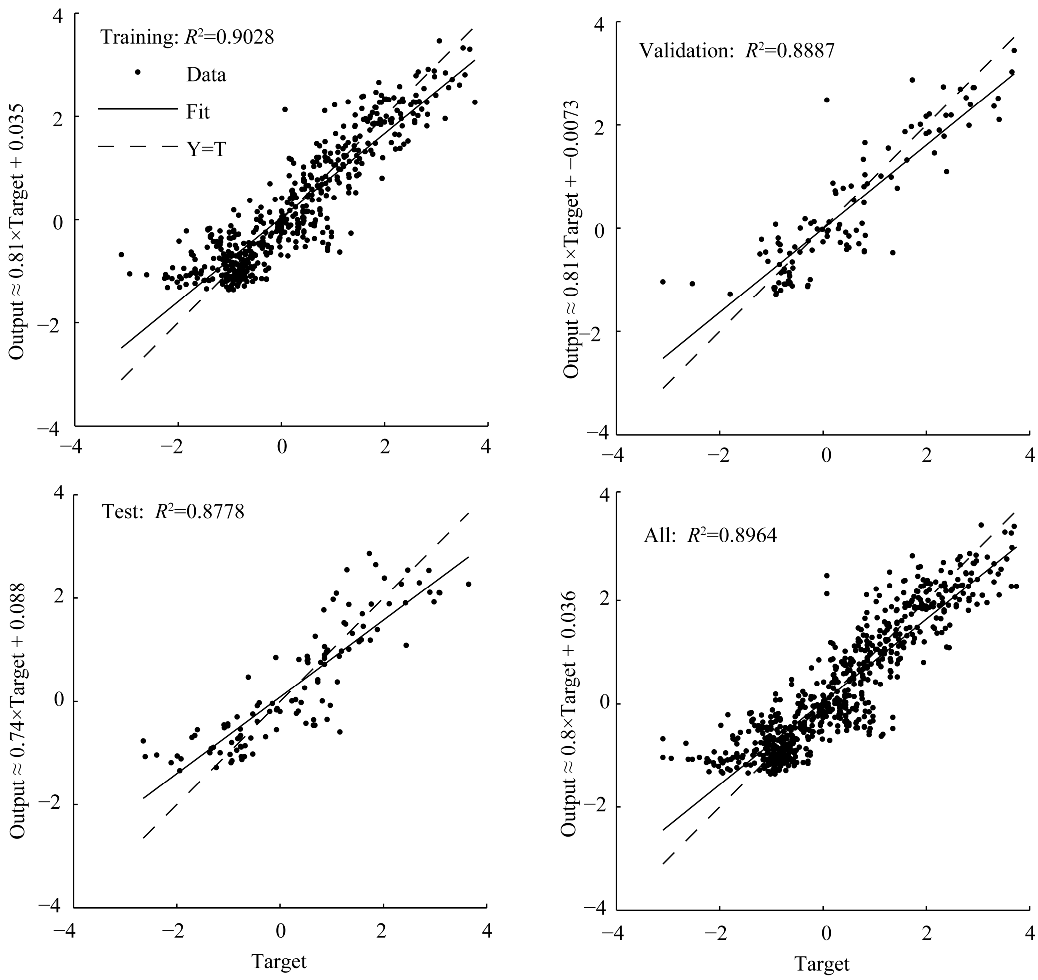

Fig. 5 Reliability of determining F_c by pH and T_{as} using the cross-validation in a back- propagation network

To highlight the specialty of soil respiration in an alkaline area (different from general carbonate ecosystems), we did not include the known non-biological processes, such as the subterranean ventilation of CO_2 (Serrano-Ortiz et al., 2010), dissolution of soil carbonates (Gombert, 2002; Kowalski et al., 2008) and groundwater recharge of dissoluble carbon (Scanlon et al., 2006), in the concept of soil inorganic respiration. But we did include these factors in the hypothetical system (short arrows in the left side of Fig. 4). We hypothesized that these known non-biological processes are not strong enough to affect the temperature sensitivity of soil respiration. The inclusion of all factors is complicated and worthy of further research.

The results in the present study suggest a significant impact of pH on soil respiration (F_c), with a focus on alkaline soils (pH: 8.5–10.4). Previously, a series of publications investigated the significance of pH on F_c, and most researches focused on non-alkaline areas (pH<7). In the acidic forest soil (pH: 3.8–6.0), the soil pH was positively correlated with the soil CO_2 fluxes (Laskowshi, 2003). It was also demonstrated in a subsequent investigation of acid agriculture soil (pH: 3.4–6.8) that a significant positive correlation existed between the pH and the soil basal respiration (Kermitt, 2006). All these studies suggested the inclusion of soil alkalinity as a main determinant in the empirical modeling of soil respiration. Therefore, the soil pH can be a significant factor to determine soil respiration in both alkaline and non-alkaline soils, and we strongly suggest the inclusion of soil pH in the Q_{10} model to develop a more reliable model for soil respiration experiments on alkaline or non-alkaline soils worldwide.

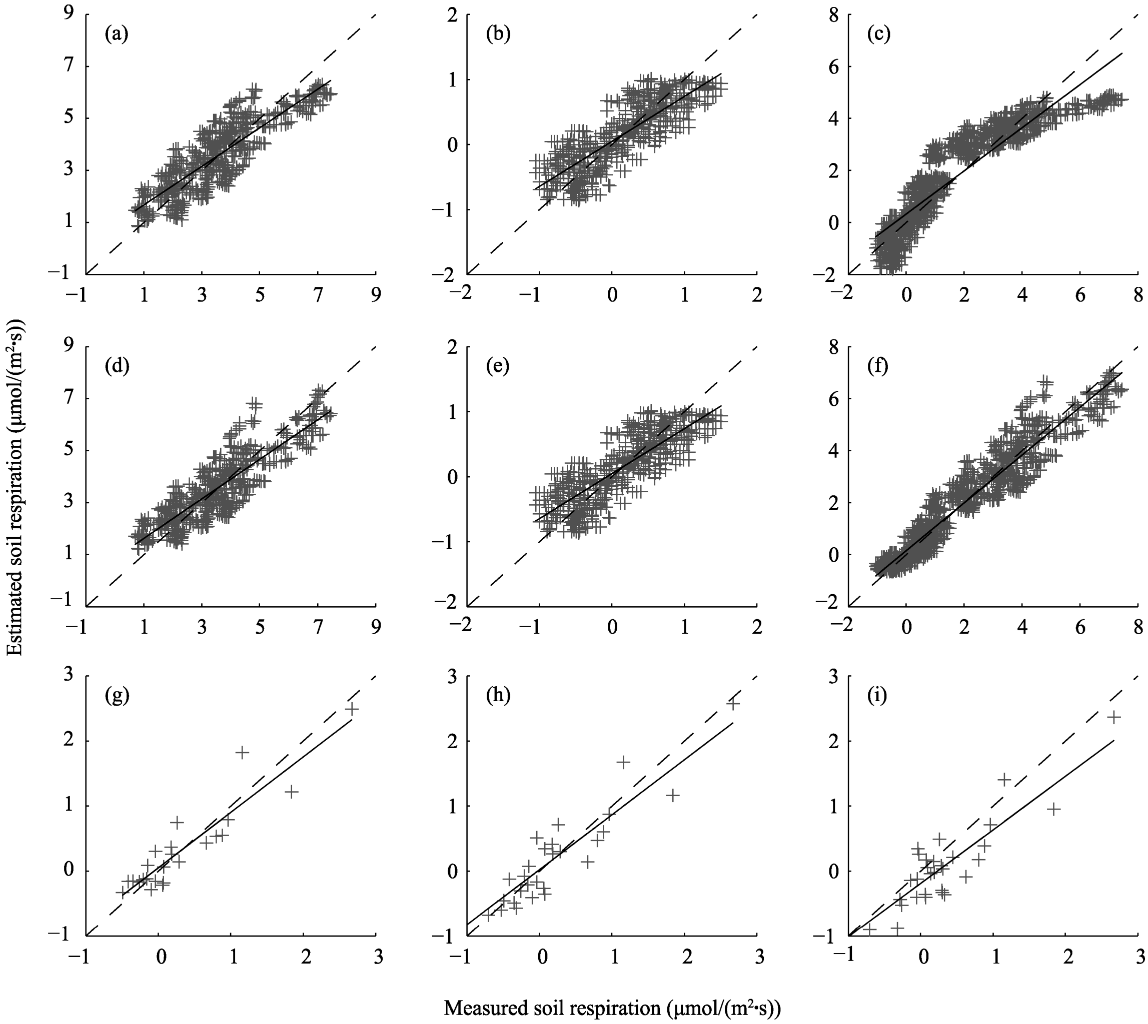

Fig. 6 Performance of Eq.3 with linear f(pH) (a–c) and exponential f(pH) (d–f, g–i) on a site scale (a, d: farmland; b, e: desert; c, f: farmland+desert) and a regional scale (g: Sangong River Basin; h: Sangong River Basin+Manas River Basin; i: Sangong River Basin+Manas River Basin+Laboratory)

4 Conclusion

Soil pH, soil volumetric water content at 0–5 cm (θ_s) and air temperature at 10 cm above the soil surface (T_{as}) are three main determinants of soil CO_2 flux (F_c) in alkaline soils of arid areas. F_c has a reduced sensitivity to soil temperature at 0–5 cm (T_s). The model $F_c=R_{10}Q_{10}^{(Tas-10)/10}+r_7q_7^{(pH-7)}+\lambda T_{as}+\mu\theta_s+e$ has a good prediction of F_c and presents an approximate method to quantify the contribution of soil abiotic CO_2 exchange to F_c. Analyses in the present study suggest that soil biotic and abiotic CO_2 exchange have equal contributions to F_c, and therefore soil abiotic CO_2 exchange is a crucial component in the carbon balance in alkaline soils of arid areas.

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